2017-02

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Kong, D

10.1007/s11356-016-7975-4
Environmental Science and Pollution Research
Springer Science and Business Media LLC

Environmental impact assessments of the Xiaolangdi Reservoir on the most hyper-concentrated laden river, Yellow River, China

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Abstract: The Yellow River is the most hyper-concentrated sediment-laden rivers in the world. Throughout recorded history, the Lower Yellow River (LYR) experienced many catastrophic flood and drought events. To regulate the LYR, a reservoir was constructed at Xiaolangdi that became operational in the early 2000s. An annual water-sediment regulation scheme (WSRS) was then implemented, aimed at flood control, sediment reduction, regulated water supply, and power generation. This study examines the eco-environmental and socio-environmental impacts of Xiaolangdi Reservoir. In retrospect, it is found that the reservoir construction phase incurred huge financial cost and required large-scale human resettlement. Subsequent reservoir operations affected the local geological environment, downstream riverbed erosion, evolution of the Yellow River delta, water quality, and aquatic biodiversity. Lessons from the impact assessment of the Xiaolangdi Reservoir are summarized as follows: (1) the construction of large reservoirs is not merely an engineering challenge, but must also be viewed in terms of resource exploitation, environmental protection, and social development; (2) long-term systems for monitoring large reservoirs should be established, and decision makers involved at national policy and planning levels must be prepared to react quickly to the changing impact of large reservoirs; and (3) the key to solving sedimentation in the LYR is not Xiaolangdi Reservoir but instead soil conservation in the middle reaches of the Yellow River basin. Proper assessment of the impacts of large reservoirs will help promote development strategies that enhance the long-term sustainability of dam projects.

Keywords: Dam; Hyper-concentrated river; Xiaolangdi Reservoir; Sustainability

1 Introduction

1.1 Motivation for this study

From the early 20th Century, dams and reservoirs have been constructed along many of the world's large rivers to exploit water resources and manage flood risk. According to the World Commission on Dams, about 45,000 large dams and an estimated 800,000 small dams had been built worldwide by the end of the 20th Century, obstructing over 65% of freshwater flow from the land to the oceans (WCD, 2000). In ancient times, dams were built for the purpose of water supply or irrigation. As civilizations developed, the demand for water increased and to this was added demands for flood control, improved navigation, and power generation which further encouraged dam construction. In contemporary times, most of the world's large rivers have been dammed to generate power in order to help meet the increasing global demand for renewable energy. Through their construction and operation, dams play a direct role in river management, while having an indirect effect on the aquatic environment of river systems. Taken together, these effects and their frequently negative consequences for river behavior and aquatic environment are attracting increasing concern. Among other initiatives, the recent Vienna Declaration made in 2011 (http://worldslargerivers.boku.ac.at) has drawn attention to the importance of protecting the world's large rivers against the negative impacts of future changes and encourages river basin management agencies to explore ways of restoring large rivers to their more natural state.

Improved understanding is therefore required for the wide-ranging impacts of dams on large rivers and the potential impacts of future dams. With this in mind, the paper examines the impact of Xiaolangdi Reservoir on the Lower Yellow River (LYR). Constructed 130 km downstream of Sanmenxia (Fig. 1), the Xiaolangdi Reservoir represents the most recent large-scale engineering project that has been implemented to manage severe sediment-related problems afflicting the LYR.

1.2 Problems besetting the LYR

The Yellow River (Fig. 1a) is the fifth longest river in the world. It is of great cultural importance to China, with the LYR colloquially known as the "the cradle of Chinese civilization" having been the most prosperous region of China in early Chinese history (Yu, 2002). The river is also known as "China's sorrow", owing to the many flood disasters that occurred throughout recorded history commencing with the Great Flood at about 1920 BCE (Wu et al. 2016), and more recently exacerbated by the riverbed elevation occurring above the level of the surrounding North China Plain (Chen et al., 2012b; Yu et al., 2013). The middle section of the Yellow River flows through the easily eroded Loess Plateau region, from which large amounts of sediment are delivered to the river. As the river exits the Loess Region and enters the North China Plain, its longitudinal slope reduces markedly (Fig. 1). During the 1950s-1970s, before the introduction of widespread soil and water conservation works within the Loess Plateau, the construction of upstream dams along the river and its tributaries, and a trend towards lower annual precipitation (Wang et al., 2006; Wang et al., 2007a), the Yellow River carried a very high sediment load. According to the Yellow River Conservancy Commission (YRCC), the mean annual suspended sediment concentration at Sanmenxia was ca. 35.6 kg m^{-3}, with the maximum value of ca. 63.8 kg m^{-3}. These suspended sediment concentrations were the highest recorded in any major world river and as such the LYR provided a classic example of a hyper-concentrated river. About 896 km further downstream at Lijin (Wang et al., 2007b), close to the river delta and its outflow to Bohai Bay, the mean annual sediment load of the river during the same period was ca. 1101 Mt $year^{-1}$. The reduction in load between Sanmenxia and Lijin primarily reflected deposition of sediment as the river flowed across the North China Plain with its reduced gradient. Throughout history, the river frequently avulsed when in flood, with the channel migrating north and south and sediment being deposited across much of the North China Plain (Chen et al., 2012b). Such floods caused huge numbers of fatalities, destroyed, and ruined agricultural land. Dyke construction was the primary approach taken to reduce such flood problems over past millennia, with the systematic construction of dykes first taking place along the LYR in the Warring States Period (475-221 BC) (Xu, 1998). The dykes helped stabilize the river's course, so much so that the river has maintained its present course since 1947. The dykes are currently up to 14 m high. However, deposition of sediment within the channel and the zone between the dykes has caused the bed elevation to increase progressively. The associated increase in water level has important implications for flood control.

Figure 1

Early in 1935, several river engineers and experts proposed the construction of Sanmenxia

Dam. As a multi-purpose project for flood control, hydropower, irrigation, navigation, and ice jam control, Sanmenxia Dam was the first large dam ever built on the Yellow River. The initial reservoir capacity was 35.4×10^9 m^3, and it controlled 89% of the runoff and 98% of the sediment coming into the LYR (Wang et al., 2005). Following completion of the dam, severe sedimentation problems became evident immediately after impoundment. Within 18 months of operation, 93% of the incoming sediment was trapped in the reservoir, representing a release efficiency of only 7%. The reservoir lost 17% of its storage capacity of 9.75×10^9 m^3 below an elevation of 335 m and 26% of its storage capacity of 5.96×10^9 m^3 below an elevation of 330 m due to sedimentation (Wang et al., 2005). The most serious adverse effect caused by the impoundment of water at the Sanmenxia Reservoir was sedimentation in the lower Wei River which increased flood risk in Shaanxi province. Sanmenxia Dam created unanticipated backwater conditions extending tens of km upstream during floods, reducing the sediment transport capacity of the Yellow River and promoting sediment deposition upstream of the constricted Tongguan reach. During the 1960s, the riverbed elevation rose 5 m at Tongguan hydrological station (Fig. 2). Consequently, Sanmenxia Dam was modified twice and its operation-mode changed several times to incorporate lateral diversion tunnels and bottom sluices that would allow sediment to pass through the dam. Although these modifications limited further riverbed rise at Tongguan in the subsequent half century, the official view is that Sanmenxia dam failed to meet its initial objectives (Wang et al., 2005). In the subsequent few decades, many large dams were continuously built in the mainstream of Yellow River, including Longyangxia, Liujiaxia, Qingtongxia and Wanjiazhai. Most of these reservoirs are located on the middle of upper Yellow River, play a positive role in controlling flood and intercepting sediment for the LYR.

Figure 2

Further attempts to reduce flood problems along the LYR over the past 50 years have included the construction of further dams, flood diversion projects, and widespread implementation of soil and water conservation measures throughout the Loess Plateau region. The Guxian and Luhun dams on Luohe and Yihe River now assist Sanmenxia dam in flood control. The Dongping lake detention project enables floodwater to be diverted from the main Yellow

River into embanked areas, ensuring that the flood magnitude does not exceed the flood discharge capacity of the downstream channel. Soil and water conservation measures in the Loess Plateau region include the introduction of grassland, afforestation, and land terracing. By the end of 2007, the preliminary management area of soil and water conservation was 225.6×10^9 m^2, including 119.5×10^9 m^2 of afforestation and 36.7×10^9 m^2 of land terracing (Kong et al., 2016). According to the statistics of the Soil and Water Conservation Bulletin in 2010, about 350 - 450×10^6 t per annum of sediment was prevented from entering the Yellow River. Even so, the sediment concentration in the Yellow River still exceeds the sediment transport capacity of the river channel in its lower reaches.

The LYR faced other challenges beyond sediment reduction and flood control. As China's socio-economic development flourished from the late 1970s onwards, water consumption increased greatly in the LYR basin, so much so that water usage had to be regulated in both dry and rainy seasons. Energy demand also grew. In April 1991, the Xiaolangdi Multipurpose Dam Project was approved at the Fourth Session of the Seventh National People's Congress, China.

1.3 The Xiaolangdi Dam

The Xiaolangdi Dam is located at the mouth of the final gorge in the middle reach of the Yellow River, approximately 40 km north of Luoyang, Henan Province, and 130 km downstream of Sanmenxia Dam (Fig 1). This location is key to flood control and sediment management of the downstream reaches of the LYR. The catchment area above Xiaolangdi Dam is 69.42×10^6 km^2, which represents approximately 92% of the entire Yellow River basin. Construction of Xiaolangdi Dam commenced in September 1991 and was completed by the end of 2001. Xiaolangdi Reservoir began to storage water in 1999. The crest of the dam is 281 m above sea level, and the maximum water level is 275 m above sea level (Fig. 3). The total capacity of the reservoir is 12.65×10^9 m^3, which includes 7.55×10^9 m^3 for sediment storage and another 5.1×10^9 m^3 allocated to flow regulation and electricity generation. Its construction consumed a vast amount of manpower and material resources. The World Bank provided a loan of 1 billion US$, and technical and managerial support (Wang et al., 2013a). According to the statistical Yearbook of the YRCC, the construction of Xiaolangdi Reservoir consumed 94.78×10^6 m^3 of earth, 3.48×10^6 m^3 of concrete, and 30 000 tons of steel, the total investment costing ¥34.02 billion (5 billion US$). The

Xiaolangdi Dam comprised one of the most challenging construction projects in the history of water-conservancy.

Figure 3

In meeting its original objectives, the dam brought about important changes to the flow and sediment regime of the LYR and to its channel. These and other more indirect effects, including changes to the delta, as well as ecological and social consequences of the dam construction and operation, are reviewed below.

2 Operation of the Xiaolangdi dam

2.1 Flood reduction

The primary objective of the Xiaolangdi dam is flood and ice-jam control, in which it is greatly assisted by both its location and the large size of its upstream reservoir. As the last large reservoir ahead of the North China Plain, the Xiaolangdi Reservoir stores floodwater not only from reaches between Sanmenxia and Xiaolangdi but also from reaches upstream of Sanmenxia. Consequently, Xiaolangdi Reservoir has enhanced flood control in the LYR. For example, should a 1000-year flood occur and Xiaolangdi Reservoir be operated in conjunction with the Sanmenxia, Guxian, and Luhun Reservoirs, the discharge at Huayuankou gauging station would not exceed the present flood control standard of 22,000 m^3/s; should a 100-year flood occur, the discharge at Huayuankou would be below 15,000 m^3/s and it would not be necessary to utilize the Dongping Lake water-detention area.

Fig. 4 illustrates schematically the operating strategy for controlling water levels in Xiaolangdi Reservoir. Since the completion of Xiaolangdi Dam, a water-sediment regulation scheme (WSRS) has been conducted annually by the YRCC to prevent downstream flooding and siltation. Just prior to the start of the rainy season (July to October), the water level in the reservoir is reduced to below the flood-control level of 225 m in order to free up storage space (Yu et al., 2013). During the wet season, excess water is stored in the reservoir thereby protecting downstream reaches by lowering the potential flood peak. In 2003, the Yellow River experienced six flood events in the Weihe River Valley. Even so, flood peaks in the main river and inflows from the Weihe, Lihe, Luohe, and Qinhe tributaries were reduced through joint regulation by the Xiaolangdi, Sanmenxia, Luhun and Guxian Reservoirs; the peak discharge at Huayuankou gauging station was about 2500 m^3/s, and inundation of large areas of the floodplain was avoided.

Figure 4

2.2 Sediment reduction

Most dams are effective sediment traps (Walling, 2008). With a dam height of 154 m and a sediment storage capacity of 7.55 × 10^9 m^3, a major objective of Xiaolangdi Reservoir is to intercept and store sediment arriving from the Loess Plateau and thus alleviate channel sedimentation problems in the LYR downstream (Ran et al., 2013). Hyper-concentrated flows transport large amounts of sediment into the reservoir from upstream reaches. When the energy of the flow reduces on entering the reservoir, most of the sediment load is deposited. From the perspective of sediment storage, the anticipated life of Xiaolangdi Reservoir was 18-20 years (Chen et al., 2015). However, by December 2014, about 3.2 × 10^9 m^3 of sediment had been trapped in the reservoir since its commissioning in 1999 (Fig. 5), accounting for about half of the total storage capacity. The huge reduction in sediment load significantly mitigated against the rise in downstream riverbed elevation.

Figure 5

Sediment deposited in the downstream reaches was further reduced by flushing during WSRS. According to statistical data in the Bulletins of Chinese River Sediment published by the Ministry of Water Resources of the People's Republic of China, the total volume of sediment deposited in the LYR was approximately 5.44×10^9 m^3 during the period from October 1951 to October 2000, corresponding to average annual sediment deposition of 111×10^6 m^3. After the Xiaolangdi Reservoir began operation, the situation reversed. Table 1 lists the segmented erosion and deposition values for the LYR. It can be seen that the main river channel in the lower reaches was fully scoured between October 2000 and October 2014, with a total erosion volume of 1.857×10^9 m^3 and an average annual erosion volume of 132.6×10^6 m^3.

Table 1

2.3 Water supply

With a water-regulation capacity of 5.1×10^9 m^3, Xiaolangdi Reservoir controls flooding during the wet season and regulates runoff during the low-flow, dry season. This large capacity ensures water supply to cities and villages along the LYR throughout the dry season. By analyzing river discharge observations from 1986 to 1997 taken at Huayuankou hydrological station, Ren et al. (2002) found that the cumulative flow discharge in the wet season was just under half the cumulative annual runoff, with an August maximum value about 3.6 times larger than the January minimum. In the decade from 2002-2012, the flow discharge at Huayuankou declined by almost 8% with the maximum monthly value occurring two months earlier than previously, due to water regulation by the Xiaolangdi Reservoir (Kong et al., 2015b). In addition to adjusting seasonal water supply to meet demand, Xiaolangdi Reservoir also effectively solved the problem of the river drying up during the dry season. During the last three decades of the last century, the LYR often ran dry owing to a decline in annual precipitation (Miao et al., 2011; Miao et al., 2012) and uncontrolled growth in water consumption by people and industry (Peng and Chen, 2010). At Lijin Hydrological station, located immediately upstream of the estuary, discharge records for the 1990s show that no flow was observed on 901 days, with a very severe drought in 1997 when no flow occurred on 226 days (Fig. 6). Once the Xiaolangdi Reservoir commenced operation, the LYR has not exhibited any further no-flow events at Lijin, even though the average annual runoff in the LYR has remained almost unchanged compared with that of 1980s-1990s (Kong et al., 2015b).

Figure 6

2.4 Power generation

Hydropower is a clean, sustainable source of electricity that is usually obtained from large dams located in deep valleys with rapid elevation drops. Xiaolangdi Dam is located at the mouth of the final gorge in the middle reach of the Yellow River, after which the elevation drop is very limited in the downstream direction (Fig. 1). A total of 6 power generation units were installed at

Xiaolangdi reservoir with an installed hydropower capacity of 1.8 GW. The power generation units from 1 to 4 of the Xiaolangdi Reservoir require water level at least above 210 m while the power generation units 5 and 6 require water level above 205 m (Li and Sheng, 2011). The designed power generation during the first 10 years' operation is no less than 4.599×10^9 kWh per year and then the magnitude increases to 5.851×10^9 kWh per year. However, the actual annual mean power generation is 4.193×10^9 kWh during the period 2000 – 2010, which is slightly lower than the designed value. This is attributed to the less runoff as well as the operation mode of Xiaolangdi reservoir (Wang and Wang, 2011).

3 Societal, environmental, and ecological impacts of Xiaolangdi Reservoir

This section provides an overview of the main societal, environmental, and ecological impacts of Xiaolangdi Reservoir.

3.1 Resettlement

Large dam projects submerge large areas of land, and the inhabitants have to be relocated and resettled. The Xiaolangdi dam is located in the densely populated lower reaches of the Yellow River basin, where many local inhabitants are employed in agriculture. Fig. 7 presents satellite images of the Xiaolangdi Reservoir region both pre- and post-construction of the dam. The relocation and resettlement programme involved four prefecture-level cities, 10 counties, 39 townships, 221 administrative villages, and more than 200,000 people (Zhang, 2008). About 301.14 km^2 of land is now occupied by the Xiaolangdi Reservoir and this previously included about 150 km^2 of farmland. To offset the losses, relocated people were provided with new houses and newly cleared farmland according to a prescribed immigration policy. However, the relocation compensation schemes fail to be fulfilled. According to survey by Tang et al. (2005), about 51% of the immigrants were dissatisfied with the housing resettlement, and about 88% thought the immigration policy was not fully implemented at least at the grass roots level. Consequently, lawmaking branch should consummate relevant law and define right and obligation, providing protection for the interests of immigrants. Even so, it is generally accepted that the dam construction increases employment opportunities for local people. After coming into operation, the reservoir could boost fishery and attract tourists because of their "lake-like" sceneries and recreational opportunities.

Figure 7

3.2 Impact on the local geological environment

The geological environment in the Xiaolangdi Reservoir region is very complex, and it is believed that any large impoundment in that region may induce a variety of geological hazards, including earthquakes, landslides, and mudslides (Sun et al., 2004). The region has deep, large faults and is prone to earthquakes, so safety issues are particularly important (Qi, 2011). Although there have been no significant signs of seismic activity induced by the filling of the reservoir, it is necessary to carry out continuous monitoring for this potential hazard. By far the greatest geological hazard has arisen from landslides and mudslides. The raised water level in the reservoir affected the stability of adjacent slopes, increasing the induced probability of landslides and mudslides both inside and outside the reservoir embankment, putting local residents and their property at risk. According to records, landslides and mudslides occurred in several residential areas when the water level in the reservoir was impounded to 275 m (Sun, et al., 2004). In addition, the operation of Xiaolangdi Reservoir impacted severely on the local coal industry (Sun et al., 2008), with earlier studies finding that the groundwater level in surrounding areas had risen dramatically after reservoir impoundment at Xiaolangdi (Sun et al., 2006; Wang, 2002), significantly hindering the extraction of coal resources (Wang et al., 2003).

3.3 Impact on runoff and sediment regime

Dams and reservoirs usually have considerable impacts on downstream runoff and sediment loads, and these effects are complicated by artificial regulation of the river discharge. Fig. 8 shows the annual water discharge and sediment load time series at Huayuankou station from 1950 to 2014. Obvious downward trends are revealed in both the annual runoff and sediment load between 1950 and 2000, suggesting that neither were particularly affected by artificial regulation at Sanmenxia. After 2000, the runoff began to exhibit a rising trend, whereas the sediment load remained relatively steady at almost zero. Two main factors account for the near disappearance of sediment load: the Soil and Water Conservation measured implemented in the middle reaches of the Yellow River (Zhao et al., 2014); drastically reduced the sediment supply to the LYR; and

WSRS at Xiaolangdi Reservoir further lowered the amount of sediment entering the LYR. As a consequence, the different trends in runoff and sediment load directly altered the sediment concentration once the Xiaolangdi Reservoir commenced operation. Fig. 9 shows the cumulative sediment load plotted against the cumulative runoff. By interpreting the gradient, the average annual sediment concentration at Huayuankou station is estimated to be about 0.026 t m^{-3} during the period 1950-1999. Fluctuations in the time series are attributed to the construction of dams and the implementation of soil and water conservation measures upstream of Huayuankou (Wang et al., 2007a). Since Xiaolangdi Reservoir began operation in 1999, the average annual sediment concentration at Huayuankou station reduced significantly to 0.004 t m^{-3}. Our previous study found that the incoming sediment concentration was the dominant factor affecting channel erosion and deposition in the LYR (Kong et al., 2015b). In short, lower sediment concentration has reversed channel deposition to channel erosion, since Xiaolangdi Reservoir began operation (Table 1).

Figure 8

Figure 9

3.4 Impact on the downstream channel

Dam construction can bring about important changes to the sediment load of a river (Walling and Fang, 2003), which can in turn lead to degradation or aggradation downstream. Comparisons between sediment budgets before and after construction of individual dams indicate that the channel downstream of a dam can experience sediment surplus or deficit (Lu et al., 2015). In the case of Xiaolangdi Reservoir, water impoundment and sediment detention have led to continuous channel degradation along the LYR. Repeated surveys of channel cross sections have shown that the cumulative volume of channel scour in the LYR reached 1.60×10^9 m^3 in the period from 1999 to 2012 (Xia et al., 2014). A direct consequence is that the river channel has been significantly deepened. Fig. 10 shows that the riverbed elevation dropped substantially after commissioning of the Xiaolangdi Dam, although the riverbed elevation still remains higher than in the 1950s. By comparing the relative lowering of the riverbed elevation at Huayuankou Station with its upstream counterparts, it can be seen that channel erosion progressively declined with distance from Xiaolangdi along the LYR.

Figure 10

Fifteen years of WSRS' operation at Xiaolangdi Reservoir has considerably modified the channel morphology of the LYR. Fig. 11 compares the cross-sectional channel morphology between 1999 and 2009. It can be seen that the average channel width (*B*) and depth (*H*) both increased in reaches upstream of Gaocun station, but that *H* increased to a greater extent than *B* in reaches downstream of Gaocun station. A combined index of cross-sectional channel morphology can be calculated as the morphological parameter $\sqrt{B}/H$. Values of this parameter reduced in all reaches in 2009 compared with 1999, indicating that the LYR channel became narrower and deeper after 10 years of reservoir' operation. Fig. 11c shows that this effect was especially marked in the upper reach of the LYR. Jiao et al. (2011) report that deepening of the riverbed has led to soil desertification in some downstream reaches because of wetland loss.

Figure 11

Channel scouring by WSRS has altered the bankfull discharge in the LYR (Xia et al., 2014), the bankfull discharge indicates flood discharge capacity and so is an important river flood index. During the last three decades of the 20th Century, periodic drying up of the Yellow River led to shrinkage of the channel in the lower reaches, resulting in a decrease in flood conveyance capacity. The bankfull discharge profiles in Fig. 12 confirm that this trend reversed after implementation of WSRS at Xiaolangdi Reservoir. By 2012, the bankfull discharge can be seen to have increased along the entire channel from Xiaolangdi to the sea; the bankfull discharge at Huayuankou was 6900 $m^3 s^{-1}$, almost twice the value in 2000.

Figure 12

Although operation of Xiaolangdi Reservoir has alleviated the pressing problems caused by heavy sedimentation and elevation of the riverbed, the present mode of operation at the reservoir is unlikely to be sustainable in terms of impact on the LYR. Fig. 10 provides evidence that the WSRS currently in operation is no longer as effective as it was initially for channel scouring in the LYR (with the riverbed elevation reducing most in the period 2002-2005, and flattening out after 2005, in accordance with finding by. Fu et al. (2012), Qi et al. (2012) and Shang et al. (2015)).

3.5 Impact on the Yellow River Delta

Reduction in the sediment load of a river can also impact on the land-sea sediment transfer (Walling, 2012). This can have important implications for deltas and coastal seas. In fact, many river deltas are sinking because of compaction and reduced sediment delivery, which increases their vulnerability to natural disturbances (Liermann et al., 2012; Syvitski and Higgins, 2012; Syvitski et al., 2009). The Yellow River Delta has immense strategic and ecological importance (Cui et al., 2009). According to Cui and Li (2011) and Wang et al. (2006), evolution of Yellow River Delta is controlled primarily by the upstream sediment load at Lijin, noting that the coastal sediment dynamics have remained reasonably constant since the late 1990s. Kong et al. (2015a) estimated that after the LYR channel was altered in 1996, annual sediment load had to attain a value of 159×10^6 t in order for the delta to retain equlibrium , which is almost exactly that observed at Lijin (158.6×10^6 t) between 2002 and 2012 (Kong et al., 2015b). The subaerial delta effectively extended and the subaqueous slope of the river mouth steepened because of accumulated sediment released during WSRS (Wu et al., 2015). Furthermore, the total wetland area increased slightly following the operation of the Xiaolangdi Reservoir (Xue et al., 2012).

In general, large reservoirs intercept sediment, resulting in significant decreases in sediment delivery to estuaries. However, this did not occur in the Yellow River estuary despite the large volumes of sediment trapped by Xiaolangdi Reservoir (Fig. 5). Sediment delivered to the river mouth since the operation of Xiaolangdi Reservoir mainly consists of sediment previously deposited in the LYR (Kong et al., 2015c). Although this implies it is feasible to maintain the delta through transport of sediment from the LYR, such an approach is not likely to be sustainable in the long term. Coarsening of the riverbed in the LYR may make future channel erosion more difficult, which may in turn result in reduced sediment delivery to the estuary (Miao et al., 2016).

3.6 Impact on water quality

Reservoir construction disrupts the natural flow of a river, and can have a knock-on effect on water quality. Xiaolangdi Dam has a very important on water quality in the Yellow River according to location and associated impact mechanisms. Upstream of Xiaolangdi Reservoir and at the reservoir itself, interception of water by the dam caused the flow rate to drop substantially and residence time to increase, leading to reduced diffusion and biodegradation of pollutants in the water body (Shi et al., 2007). The resulting decrease in self-cleansing capacity of the river encouraged water eutrophication and algal blooms (Su et al., 2013; Wang et al., 2008). This was exacerbated by temperature stratification within the reservoir (Wang et al., 2007c). Downstream of Xiaolangdi Reservoir, water quality worsened during the initial period of reservoir operation but later improved owing to dilution and flushing (Shi et al., 2006; Shi et al., 2007) benefiting water abstraction for domestic and agricultural use. It has also been found that water–sediment regulation might reduce the long-term retention of polycyclic aromatic hydrocarbons (PAHs) in the reservoir (Dong et al., 2015). However, the environmental risk posed by PAHs as well as other contaminants downstream of the reservoir might increase during the flushing process. Therefore, the effect of water–sediment regulation on the bioavailability of, and hence environmental risk from hydrophobic organic compounds (HOCs) should be considered in the operation and management of Xiaolangdi Reservoir in the future.

Inevitably, the quality also altered of river water discharged into the Bohai Sea. Water-sediment regulation had a strong impact on the N_2O distribution in the estuary. 55.9% of the annual N_2O input from the Yellow River to the Bohai Sea occurred during WSRS, even though the corresponding water discharge accounted for only 26.9% of total runoff (Ma et al., 2016). Abundant nutrients were transported to the coastal waters, and the nutrient imbalance was disturbed, impacting severely on the adjacent Bohai Sea ecosystem (Liu, 2015). Before the operation of Xiaolangdi reservoir, it was reported that the Yellow River annually transported 0.2 million tons of dissolved organic carbon (DOC) and 6.1 million tons of particulate organic carbon (POC) to the Bohai Sea (Zhange et al., 1992). The DOC and POC fluxes in 2013 have decreased by 45.0% and 91.8%, respectively, suggesting that the organic carbon (OC) flux decreased after the operation of Xiaolangdi Reservoir (Xia et al., 2016).

3.7 Impact on aquatic biodiversity

It is well known that construction of large reservoirs influences the biodiversity of both terrestrial and aquatic species (Liermann et al., 2012). Large reservoirs submerge the natural habitat and hence permanently affect the surrounding terrestrial biodiversity. However, terrestrial animals that are forced to migrate can usually resettle on higher ground, resulting in little overall effect on their numbers. Reservoir construction generally has a more significant influence on aquatic biodiversity, especially freshwater fish. In the middle reaches of the Yellow River, average fish resources reduced by 50% following WSRS by Xiaolangdi Reservoir, with a concomitantly large reduction in the diversity index (Zhu et al., 2012). This is primarily attributed to large shoals of fish beaching during the periods of WSRS, leading to denudation of large areas of spawning and feeding grounds (Zhu et al., 2012). For example, the distribution of Yellow River carp has decreased drastically due to the loss of spawning and feeding grounds. There has also been a noticeable decrease in average fish size (Chen, 2013; Zhang et al., 2012). Since its initial operation, the WSRS flow regimes at Xiaolangdi Reservoir have been altered, with changes to the flow amplitude, magnitude, frequency, duration, and timing. Most of the resulting flow regimes no longer meet the ecological requirements of Yellow River carp (Jiang et al., 2010). Large-scale fish death events have occurred during the periods of WSRS at Xiaolangdi Reservoir, mainly due to acute hypoxia caused by rapidly flowing water with high sediment concentration (Baiyin et al., 2012; Sun et al., 2012). Field surveys in 2010 showed that dissolved oxygen decreased rapidly owing to the increase in suspended sediment concentration and that the dead fish were members of 10 species (Baiyin et al., 2016). By modelling the severity of the ill effects experienced by the fish, Baiyin et al. (2016), estimated the sediment flushing exercise in 2010 to have caused fish mortality of up to 20%. Indeed, several fish species, such as the bronze gudgeon and *coilia ectenes*, are either extinct or on the brink of extinction in the Yellow River, both upstream and downstream of Xiaolangdi Reservoir (Lv et al., 2012).

To protect the aquatic biodiversity, some operational strategies would be adopted: (1) construct additional passage or channel for fish migration; (2) develop strict prohibited fishing policy to prevent overfishing; (3) build artificial fish nest to ensure the normal breeding of fish, such as artificial reef and artificial spawning grounds; (4) carry out long-term monitoring and controlling for the water quality to protect the living environment.

4 Discussion

4.1 Future challenges for Xiaolangdi Reservoir

Since Xiaolangdi Reservoir first commenced operation, it has played a significant role in harnessing the LYR in terms of flood control, sediment reduction, water supply, and power generation. Previous studies have shown that the degree of channel deposition in the LYR depends mainly on the incoming sediment concentration at Xiaolangdi station while the total sediment feed at the Lijin station is the dominant factor influencing the evolution of the YRD (Kong et al., 2015a; Kong et al., 2015b). Theoretically, the bi-objective (channel scouring and delta maintenance) can be achieved concurrently by regulating the incoming water and sediment load at the Xiaolangdi station (Kong et al., 2015c). However, how to reasonably optimize the WSRS and effectively implement the bi-objective (or future multi-objective), needs careful consideration.

Although sedimentation in the LYR has improved, the phenomenon of the secondary suspended river remains a very serious problem. There is concern that Xiaolangdi Reservoir may not be able to eradicate the perched river before the reservoir itself silts up. As indicated in Fig. 5, a huge amount of sediment has already been deposited in Xiaolangdi Reservoir. Even though the deployment of WSRS has increased the design life of the Xiaolangdi Reservoir, the reservoir cannot escape its eventual fate. As can be seen in Fig. 13, the reservoir bed elevation has risen significantly after 15 years of trapping sediment. And of course sedimentation leads directly to a decline in storage capacity of the reservoir. It is inevitable that if the flow of sediment into the reservoir continues, Xiaolangdi Reservoir will eventually be filled with sediment—a fate that befell Sanmenxia Reservoir. Given that Xiaolangdi Reservoir may be the last reservoir capable of protecting the LYR, it is critical that its functionality be maintained for as long as possible. If Xiaolangdi reservoir loses its function finally, great deal of manpower and material resources have to be required for manually adjusting the river channel in the LYR.

Figure 13

We believe that the fundamental way to solve sedimentation issues in the lower reaches of the

Yellow River is through reduction of sediment mobilization in the middle Yellow River basin. It is therefore more important to promote soil and water conservation in the middle Yellow River basin than to build more reservoirs. Although China's Grain for Green project has greatly increased vegetation cover on the Loess Plateau since 1999 and erosion has returned to historically lower levels (Chen et al., 2015), the annual sediment discharge into the Yellow River from the Loess Plateau is arguably still greater than can be safely transported by the Yellow River. The Yellow River may be more vulnerable today than in the past, given that its features have been changed irreversibly. Further soil and water conservation measures on the Loess Plateau should be implemented to reduce further erosion of the middle Yellow River basin.

4.2 Lessons learned from Xiaolangdi Reservoir

The overall impacts of the Xiaolangdi Reservoir are complex and dynamically changing, and it is therefore not possible to give a simple view of its performance in terms of advantages and disadvantages. Xiaolangdi Reservoir provides a useful case study whose lessons translate to other large reservoirs, and poses challenges central to river resource exploitation, environmental protection and social development (Wang et al., 2013a). The decision to construct a large dam involves economic feasibility assessment that considers resources availability, technological capacity, financing, and market conditions, and environmental risk assessment. Much research has focused on the environmental impact of large dams (Fan et al., 2015) including studies on the immediate post-construction changes to terrestrial and aquatic ecosystems (Li et al., 2013; Liermann et al., 2012), geological features (Ta et al., 2008), and water quality (Kurunc et al., 2006). Although not considered in the design of the Xiaolangdi Dam, we recommend that future environmental assessment should also address long-term sustainability impacts, including greenhouse-gas emission rates, regional climate change, and the relationship between reservoir size and earthquake frequency. Long-term impacts on global environmental sustainability must not be neglected, given the substantial proportion of the world's freshwater presently stored behind large-dam reservoirs. In China, the importance of social equity in dam projects has only become recognized in recent years. Even though large dams have been used as an important means of social development, the distribution of benefits and costs has usually not been equitable (Tilt et al., 2009; Wang et al., 2013b). Resolution of this complex problem will require interdisciplinary knowledge and collaboration.

In general, the future of large dams in China is shaped by interests held by various stakeholders, and should account for complex inter-relationships between economic, societal, institutional, and environmental domains. Overriding principles based on fairness and equity need to be put in place to judge whether or not new dams should be built. These principles must be holistic, encompassing all relevant human and natural factors, and respecting and protecting the interests of different stakeholder groups (Miao et al., 2015). Only by ensuring participation by all key stakeholders, transparency during decision-making, and accountability in the implementation of new projects can the process be scientific, efficient, and fair (Wang et al., 2013a).

Moreover, post-evaluation system for assessing environmental impact of the reservoir should be established. Current environmental monitoring and management mainly focus on the stage of project design and construction, and tend to be neglected after the project completion. Long-term monitoring and evaluation for the impact of dam projects is necessary and of great significance. Timely adjustment and remedial measures not only reduce the adverse impacts and losses caused by the reservoir project, but also extend the operating life of the reservoir.

5 Summary

The present paper has examined the case study of Xiaolangdi Reservoir, China, a major water regulation project located near the upstream boundary of the Lower Yellow River (LYR), an example of one of the world's most sediment-laden river. Xiaolangdi Reservoir has made significant contributions to flood risk management and stability of the LYR, water supply, and hydropower generation. However, the construction and operation of the reservoir have caused water quality, to deteriorate, biodiversity to reduce, and the geological environment to be less stable. Our findings indicate that Xiaolangdi Reservoir cannot guarantee the continuance of the present functional performance of the LYR into the future. We believe the key to solving issues in the lower reaches of the river lies in the management of its middle reaches. The necessity of building large reservoirs should be reconsidered, and mechanisms developed for the comprehensive assessment of the impact of large reservoirs.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 41622101; No. 91547118) and the National Key Research and Development Program of China (No. 2016YFC0501604; No. 2016YFC0402407). We are grateful to the Yellow River Conservancy Commission of the Ministry of Water Resources (http://www.yellowriver.gov.cn/) for collecting and archiving the dataset of population and water conservancy facilities in the Yellow River Basin, and to the organization of the Yellow River (http://www.yellowriver.org/) for collecting and archiving the soil and water conservation data in the Yellow River Basin.

References

Baiyin, B.L.G., Xu, F.R., Chen, X.R., Chen, W.X., 2012. Impact of sediment flushing of Xiaolangdi Reservoir on downstream fish. Shuili Xuebao, 43(10): 1146-1153.

Baiyin, B.L.G., Xu, F.R., Chen, X.R., Wang, X.Y., Chen, W.X., 2016. Acute impacts of reservoir sediment flushing on fishes in the Yellow River. Journal of Hydro-environment Research. DOI:10.1016/j.jher.2015.11.003

Chen, J.G., Zhou, W.H., Chen, Q., 2012a. Reservoir sedimentation and transformation of morphology in the lower yellow river during 10 year's initial operation of the Xiaolangdi reservoir. Journal of Hydrodynamics, Ser. B, 24(6): 914-924.

Chen, J.G., Zhou, W.H., Han, S.S., 2015. Ponderations and suggestions on operation mode of Xiaolangdi Reservoir in its second stage of sediment retaining. Journal of Hydraulic Engineeering, 46(5): 574-583.

Chen, Y., Syvitski, J.P., Gao, S., Overeem, I., Kettner, A.J., 2012b. Socio-economic impacts on flooding: a 4000-year history of the Yellow River, China. Ambio, 41(7): 682-98.

Chen, Y.P., Wang K., Lin Y., Shi W., Song Y., He X., 2015. Balancing green and grain trade. Nature Geoscience, 8(10): 739-741.

Chen, Y.Y., 2013. The biodiversity of fish and protection measures of Yumenkou to Sanmenxia in mainstream of Yellow River. Journal of Anhui Agricultural Sciences, 15: 055.

Cui, B.L., Li, X.Y., 2011. Coastline change of the Yellow River estuary and its response to the sediment and runoff (1976–2005). Geomorphology, 127(1-2): 32-40.

Cui, B.S., Yang, Q.C., Yang, Z.F., Zhang, K.J., 2009. Evaluating the ecological performance of wetland restoration in the Yellow River Delta, China. Ecological Engineering, 35(7): 1090-1103.

Dong, J., Xia X, Wang M., Lai Y., Zhao P., Dong H., Zhao Y., Wen J., 2015. Effect of water–sediment regulation of the Xiaolangdi Reservoir on the concentrations, bioavailability, and fluxes of PAHs in the middle and lower reaches of the Yellow River. Journal of Hydrology, 527: 101-112. DOI:10.1016/j.jhydrol.2015.04.052

Fan, H., He, D.M., Wang, H.L., 2015. Environmental consequences of damming the mainstream Lancang-Mekong River: A review. Earth-Science Reviews, 146: 77-91.

Fu, C.L., Li, Q.Y., Wang, Q.B., Li, Q., 2012. Influence of water and sediment regulation of the Xiaolangdi reservoir on the channel scouring and silting of lower reaches of the Yellow River. Journal of Water Resource & Water Engineering, 23(05): 173-175.

Jiang, X.H., Zhao, W.H., Zhang, W.G., 2010. The impact of Xiaolangdi Dam operation on the habitat of Yellow River Carp. Acta Ecologica Sinica, 30(18): 4940-4947.

Jiao, H.J., Yan, Z.P., Wang, L., 2011. Influence of Xiaolangdi reservoir to the geological environment of the lower Yellow River. Yellow River, 33(4): 63-65.

Kong, D.X. et al., 2015a. Evolution of the Yellow River Delta and its relationship with runoff and sediment load from 1983 to 2011. Journal of Hydrology, 520(0): 157-167.

Kong, D.X. et al., 2015b. The hydro-environmental response on the lower Yellow River to the water–sediment regulation scheme. Ecological Engineering, 79: 69-79.

Kong, D.X., Miao, C.Y., Wu, J.W., Jiang, L., Duan, Q.Y., 2015c. Bi-objective analysis of water–sediment regulation for channel scouring and delta maintenance: A study of the lower Yellow River. Global and Planetary Change, 133: 27-34.

Kong, D.X., Miao, C.Y., Wu, J.W., Duan, Q.Y., 2016. Impact assessment of climate change and human activities on net runoff in the Yellow River Basin from 1951 to 2012. Ecological Engineering, 91: 566-573.

Kurunc, A., Yurekli, K., Okman, C., 2006. Effects of Kilickaya Dam on concentration and load values of water quality constituents in Kelkit Stream in Turkey. Journal of Hydrology, 317(1-2): 17-30.

Li, L.G., 2009. Analysis of properties and causes of deformation of the Xiaolangdi Hydro Project dam. Advances in Science and Technology of Water Resources, 29(4): 39-43.

Li, J.P., Dong, S., Peng M., Yang, Z., Liu, S., Li, X., Zhao, C., 2013. Effects of damming on the biological integrity of fish assemblages in the middle Lancang-Mekong River basin. Ecological Indicators, 34: 94-102.

Li, G.Y., Sheng, L.X., 2011. Model of water-sediment regulation in Yellow River and its effect. Science China Technological Sciences, 54(4): 924-930.

Liermann, C.R., Nilsson, C., Robertson, J., Ng, R.Y., 2012. Implications of dam obstruction for global freshwater fish diversity. BioScience, 62(6): 539-548.

Liu, S.M., 2015. Response of nutrient transports to water–sediment regulation events in the Huanghe basin and its impact on the biogeochemistry of the Bohai. Journal of Marine Systems, 141: 59-70. DOI:10.1016/j.jmarsys.2014.08.008

Lu, X.X., Oeurng, C., Le, T.P.Q., Thuy, D.T., 2015. Sediment budget as affected by construction of a sequence of dams in the lower Red River, Viet Nam. Geomorphology, 248: 125-133.

Lv, B.B., Yang, X.Z., Wang, X.C., Xing, J.J., Zhang, J.J., 2012. The current fishery resources status of Xiaolangdi to estuary reach in mainstream of Yellow River and its protection measures. Journal of Hydroecology, 3: 015.

Ma, X., Zhang G.L., Liu, S.M., Wang, L., Li, P.P., Gu, P.P., Sun, M.-S., 2016. Distributions and fluxes of nitrous oxide in lower reaches of Yellow River and its estuary: Impact of water-sediment regulation. Estuarine, Coastal and Shelf Science, 168: 22-28. DOI:10.1016/j.ecss.2015.10.001

Miao, C.Y., Kong, D., Wu, J., Duan, Q., 2016. Functional degradation of the water-sediment regulation scheme in the lower Yellow River: Spatial and temporal analyses. The Science of the total environment, 551-552: 16-22. DOI:10.1016/j.scitotenv.2016.02.006

Miao, C.Y., Borthwick, A.G.L., Liu, H.H., Liu, J.G., 2015. China's policy on dams at the crossroads: removal or further construction? Water, 7(5): 2349-2357.

Miao, C.Y., Ni, J.R., Borthwick, A.G.L., Yang, L., 2011. A preliminary estimate of human and natural contributions to the changes in water discharge and sediment load in the Yellow River. Global and Planetary Change, 76(3-4): 196-205.

Miao, C.Y., Shi, W., Chen, X.H., Yang, L., 2012. Spatio-temporal variability of streamflow in the Yellow River: possible causes and implications. Hydrological Sciences Journal, 57(7): 1355-1367.

Peng, J., Chen, S.L., 2010. Response of delta sedimentary system to variation of water and sediment in the Yellow River over past six decades. Journal of Geographical Sciences, 20(4): 613-627.

Qi, P., Qu, S.J., Sun, Z.Y., 2012. Suggestion on optimizing flow and sediment regulations as the operational methods of the Xiaolangdi Reservoir. Yellow River, 34(1): 5-8.

Qi, Z.F., 2011. Analysis on environmental impact of Xiaolangdi Reservoir operation. Yellow River, 33(12): 97-98.

Ran, L.S., Lu, X.X., Xin, Z.B., Yang, X.K., 2013. Cumulative sediment trapping by reservoirs in large river basins: A case study of the Yellow River basin. Global and Planetary Change, 100: 308-319.

Shang, H., Sun, Z., Tian, S., 2015. Research on dry bulk density of deep sediment in Xiaolangdi reservoir. Yellow River, 37(8): 7-9.

Shi, J.Y., Zhou, Y.L., Mu, Y.Z., Zhang, N., 2006. Study on influence of operation of Xiaolangdi Reservoir to distribution of water pollution of downstream. Yellow River, 28(10): 41-42+54.

Shi, Y., Xu, Z.X., Mao, Y.X., 2007. The influence of Xiaolangdi reservoir on riverway water quality purification ability. Environmental Engineering, 25(1): 74-75.

Su, C., Zhang, J.S., Zheng, H., Li, M.H., Wang, J., 2013. Analysis on eutrophication trend of the Xiaolangdi Reservoir on the Yellow River. Yellow River, 35(6): 73-74+79.

Sun, L.Y., Baiyin, B.L.G., Niu, C.J., Li, C., 2012. Acute stress caused by sand discharging on Yellow River Carp (Cyprinus carpio) in Xiaolangdi Reservoir. Acta Ecologica Sinica, 32(7): 2204-2211.

Sun, Y.J. et al., 2008. Forecasting water disaster for a coal mine under the Xiaolangdi reservoir. Journal of China University of Mining and Technology, 18(4): 516-520.

Sun, Y.Y., Liu, F.Y., Zheng, J.R., Fu, X.T., 2004. The geological hazard types along the Yuanqu bank in the Xiao langdi Reservoir area and their preventive measures. The Chinese Journal of Geological Hazard and Control, 15(4): 34-39.

Sun, Y.Y., Wang, P.Y., Zhang, D.Z., 2006. Simple analysis on the influence of Xiaolangdi Reservoir impounding to the coal mined-out area of Jiyuan Section in reservoir area. Hydrogeology & engineering geology, 33(1): 72-75.

Syvitski, J., Higgins, S., 2012. Going under: The world's sinking deltas. New Scientist, 216(2893): 40-43.

Syvitski, J.P.M., Kettner, A.J., Overeen, I., Hutton, E.W.H., Hannon, M.T., Brakenridge, G.R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R.J., 2009. Sinking deltas due to human activities. Nature Geoscience, 2(10): 681-686.

Ta, W.Q., Xiao, H.L., Dong, Z.B., 2008. Long-term morphodynamic changes of a desert reach of the Yellow River following upstream large reservoirs' operation. Geomorphology, 97(3-4): 249-259.

Tang, G.D., Zhou, H., Yun, L., 2005. Analysis of immigrants' psychological satisfaction on the land acquisition and resettlement caused by Xiaolangdi Project. Yellow River, 27(4): 54-56.

Tilt, B., Braun, Y., He, D.M., 2009. Social impacts of large dam projects: A comparison of international case studies and implications for best practice. Journal of Environmental Management, 90: S249-S257.

Walling, D., 2008. The changing sediment loads of the world's rivers. Annals of Warsaw University of Life Sciences-SGGW. Land Reclamation, 39: 3-20.

Walling, D.E., 2012. The role of dams in the global sediment budget. IAHS-AISH publication: 3-11.

Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Global and Planetary Change, 39(1-2): 111-126.

Wang, E.Y., 2002. Influences of Xiaolangdi reservior water storage on mining activity of adjacent coal mine. China Mining Magazine, 11(3): 40-42.

Wang, Q.Z., Wang, L.L., 2011. Analysis of Power Generation Target of Xiaolangdi Hydro-junction. Water Resources & Power, 29(10): 162-164.

Wang, G., Wu, B., Wang, Z.-Y., 2005. Sedimentation problems and management strategies of Sanmenxia Reservoir, Yellow River, China. Water Resources Research, 41(9): DOI:10.1029/2004wr003919

Wang, H., Yang, Z., Saito, Y., Liu, J.P., Sun, X., Wang, Y., 2007a. Stepwise decreases of the Huanghe (Yellow River) sediment load (1950–2005): Impacts of climate change and human activities. Global and Planetary Change, 57(3-4): 331-354.

DOI:10.1016/j.gloplacha.2007.01.003

Wang, L.W., Zeng, Y., Qu, K., 2007c. Analysis of water quality change characteristic and influence in Xiaolangdi Reservoir. Journal of Water Resources & Water Engineering, 18(3): 63-65.

Wang, P., Dong, S.K., Lassoie, J.P., 2013a. The large dam dilemma: an exploration of the impacts of hydro projects on people and the environment in China. Springer Science & Business Media.

Wang, P., Lassoie, J.P., Dong, S.K., Morreale, S.J., 2013b. A framework for social impact analysis of large dams: A case study of cascading dams on the Upper-Mekong River, China. Journal of environmental management, 117: 131-140.

Wang, S.J., Hassan, M.A., Xie, X.P., 2006. Relationship between suspended sediment load, channel geometry and land area increment in the Yellow River Delta. Catena, 65(3): 302-314.

Wang, W.X., Meng, L.L., Hong, M., Yan, M.G., 2008. Analysis and evaluation on variation trend of water quality of the Xiaolangdi Reservoir. Yellow River, 30(4): 47-49.

Wang, Z.R., Liu, Q.J., Niu, S.A., 2003. Evaluation of influence of impounding and operation of Xiaolangdi Reservoir on prevention of mining water hazards. Hydrogeology & engineering geology, (5): 61-65.

Wang, Z.Y., Wu, B., Wang, G., 2007b. Fluvial processes and morphological response in the Yellow and Weihe Rivers to closure and operation of Sanmenxia Dam. Geomorphology, 91(1-2): 65-79. DOI:10.1016/j.geomorph.2007.01.022

WCD, 2000. Dams and development: A new framework for decision-making: the report of the World Commission on Dams. Earthscan.

Wu, Q., Zhao, Z., Liu, L., Granger, D.E., Wang, H., Cohen, D.J., Wu, X., Ye, M., Bar-Yosef, O., Lu, B., Zhang, J., Zhang, P., Yuan, D., Qi, W., Cai, L., Bai, S. 2016. Outburst flood at 1920 BCE supports historicity of China’s Great Flood and the Xia dynasty, Science, 353(6299): 579-582. DOI: 10.1126/science.aaf0842.

Wu, X., Bi, N., Yuan, P., Li, S., Wang, H., 2015. Sediment dispersal and accumulation off the present Huanghe (Yellow River) delta as impacted by the Water-Sediment Regulation Scheme. Continental Shelf Research, 111: 126-138. DOI:10.1016/j.csr.2015.11.003.

Xia, X.H., Dong, J.W., Wang, M.H., Xie, H., Xia, N., Li, H.S., Zhang, X.T., Mou, X.L., Wen, J.J., Bao, Y.M. Effect of water-sediment regulation of the Xiaolangdi reservoir on the concentrations, characteristics, and fluxes of suspended sediment and organic carbon in the Yellow River. Science of the Total Environment, doi: 10.1016/j.scitotenv.2016.07.015.

Xia, J.Q., Li, X.J., Li, T., Zhang, X.L., Zong, Q.L., 2014. Response of reach-scale bankfull channel geometry to the altered flow and sediment regime in the lower Yellow River. Geomorphology, 213: 255-265.

Xue, X.J., Gong, L.L., Bao, T., Jiang, X.H., 2012. Influence of Xiaolangdi reservoir on moisture conditions and landscape pattern of Yellow River delta wetland. Bulletin of Soil and Water Conservation, 32(4): 232-236.

Xu, J.X., 1998. Naturally and anthropogenically accelerated sedimentation in the Lower Yellow River, China, over the past 13,000 years. Geografiska Annaler: Series A, Physical Geography, 1998, 80(1): 67-78.

Yu, L.S., 2002. The Huanghe (Yellow) River: a review of its development, characteristics, and future management issues. Continental Shelf Research, 22(3): 389-403.

Yu Y. et al., 2013. Effects of dams on water and sediment delivery to the sea by the Huanghe (Yellow River): The special role of Water-Sediment Modulation. Anthropocene, 3, 72-82.

Zhang, J.J., 2008. Research on the Xiaolangdi immigrants' social adaptation－take the jiyuan immigrants as an example (Master's thesis, Soochow University).

Zhang, S., Gan, W.B., Ittekkot, V., 1992. Organic matter in large turbid rivers: the Huanghe and its estuary. Marine Chemistry, 38(1): 53-68.

Zhang, J.Y., Zhang J.J., Shen H.B., Lü B.B., Wang X.C., Xing J.J., 2012. Effects of water and sediment regulation at Xiaolangdi Dam on the fish assemblages from Hukou to Sanmenxia section of Yellow River. Chinese Journal of Ecology, 31(10): 2613-2618.

Zhao, G., Mu, X., Strehmel, A., Tian, P., 2014. Temporal Variation of Streamflow, Sediment Load and Their Relationship in the Yellow River Basin, China. PloS one, 9(3): e91048.

Zhu, G.Q., Zhao, R.L., Hu, Z.P., Hou, X.L., 2012. Impacts of water and sand diversion in Xiaolangdi Reservoir on fish and ecologically sensitive areas in the Middle Yellow River. Journal of Hydroecology, 33(5): 7-12.

Table 1 Erosion and deposition in the LYR from October 2000 to October 2014. Data were collected by the YRSB, and published by YRCC.

Time section	Erosion and deposition [a] (10^6 m^3)							
	XLD-HYK [b]	HYK-JHT	JHT-GC	GC-SK	SK-AS	AS-LK	LK-LJ	Total
2000.10-2001.10	-55.18	-27.84	-8.04	6.16	-2.75	5.51	4.2	-77.92
2001.10-2002.10	-21.8	-29.74	-5.59	-39.05	-2.13	-4.63	-18.42	-121.4
2002.10-2003.11	-134.4	-47.4	-41.1	-25.9	-14.5	-39.8	-58.1	-361.1
2003.11-2004.10	-28	-42.6	-28.1	-5.0	-5.3	-11.2	-13.5	-133.7
2004.10-2005.10	-23.9	-26.6	-28.9	-19.7	-11.5	-19.0	-13.5	-142.8
2005.10-2006.10	-39.5	-63.4	-7.7	-21.4	-0.1	7.4	-3.8	-128.5
2006.10-2007.10	-43.8	-44.3	-15.9	-25.2	-6.5	-13.1	-16.1	-164.9
2007.10-2008.10	-27.8	-11.0	-9.8	-16.5	-3.9	1.2	-5.9	-73.7
2008.10-2009.10	-9.5	-27.1	-20.9	-21.9	-4.5	-3.8	-4.3	-92.0
2009.10-2010.10	-29	-29.3	-12.5	-13.3	-4.0	-10.1	-9.5	-107.7
2010.10-2011.10	-33.5	-43.3	-26.1	-12.6	-6.9	-6.7	-5.8	-134.6
2011.10-2012.10	2.3	-44.2	-17.7	-15.3	-5.8	-9.3	-9.4	-99.4
2012.10-2013.10	-52.4	-26.6	-14.3	-9.2	-3.6	-6.5	-15.4	-128.0
2013.10-2014.10	-22.1	-37.0	-14.1	-12.5	0.6	1.4	-7.6	-91.3

[a] Positive values represent deposition volume, whereas negative values represent erosion volume.

[b] From October 2006, the data represent the section from Xixiayuan to Huayuankou. Xixiayuan Reservoir is located 16 km downstream of Xiaolangdi Dam.

XLD = Xiaolangdi, HYK = Huayuankou, JHT = Jiahetan, GC = Gaocun, SK = Sunkou, AS = Aishan, LK = Luokou, LJ = Lijin

Figure Captions

Fig. 1 Maps of the Yellow River drainage basin: (a) overall basin; (b) detailed map of LYR showing locations of main large reservoirs and key hydrological stations.

Fig. 2 Riverbed elevation at Tongguan station from 1950 to 2014.

Fig. 3 A typical cross-sectional view of Xiaolangdi Dam. This diagram is adapted from Li (2009).

Fig. 4 Operating strategy for controlling the water level in Xiaolangdi Reservoir. Data were collected from the Yellow River Sediment Bulletin (YRSB) published by the YRCC.

Fig. 5 Cumulative volume of sediment trapped in Xiaolangdi Reservoir since commissioning. Data collected by the YRSB and published by YRCC.

Fig. 6 No-flow days in the LYR at Lijin between 1970 and 2014.

Fig. 7 Pre-dam and post-dam satellite imagery of the Xiaolangdi Reservoir region. The remotely-sensed Landsat data was archived by the Earth Resources Observation and Science (EROS) Center (http://glovis.usgs.gov/).

Fig. 8 Annual water discharge and sediment load at Huayuankou station from 1950 to 2014.

Fig. 9 Relationship between cumulative sediment load and cumulative runoff at Huayuankou station from 1950-2014.

Fig. 10 Average riverbed elevation at Huayuankou, Sunkou and Luokou stations. The dashed lines represent the average riverbed elevation in the 1950s (Miao et al., 2016).

Fig. 11 Modification of river morphology from 1999 to 2009. This figure is based on data provided by Chen et al. (2012a). The morphological parameter is defined as $\sqrt{B}/H$ $\sqrt{B}/H$, where B and H represent the average channel width and depth respectively.

Fig. 12 Bankfull discharge profiles along the LYR in different years (Kong et al., 2015b).

Fig. 13 Evolution of: (a) bed elevation; and (b) capacity of Xiaolangdi Reservoir.

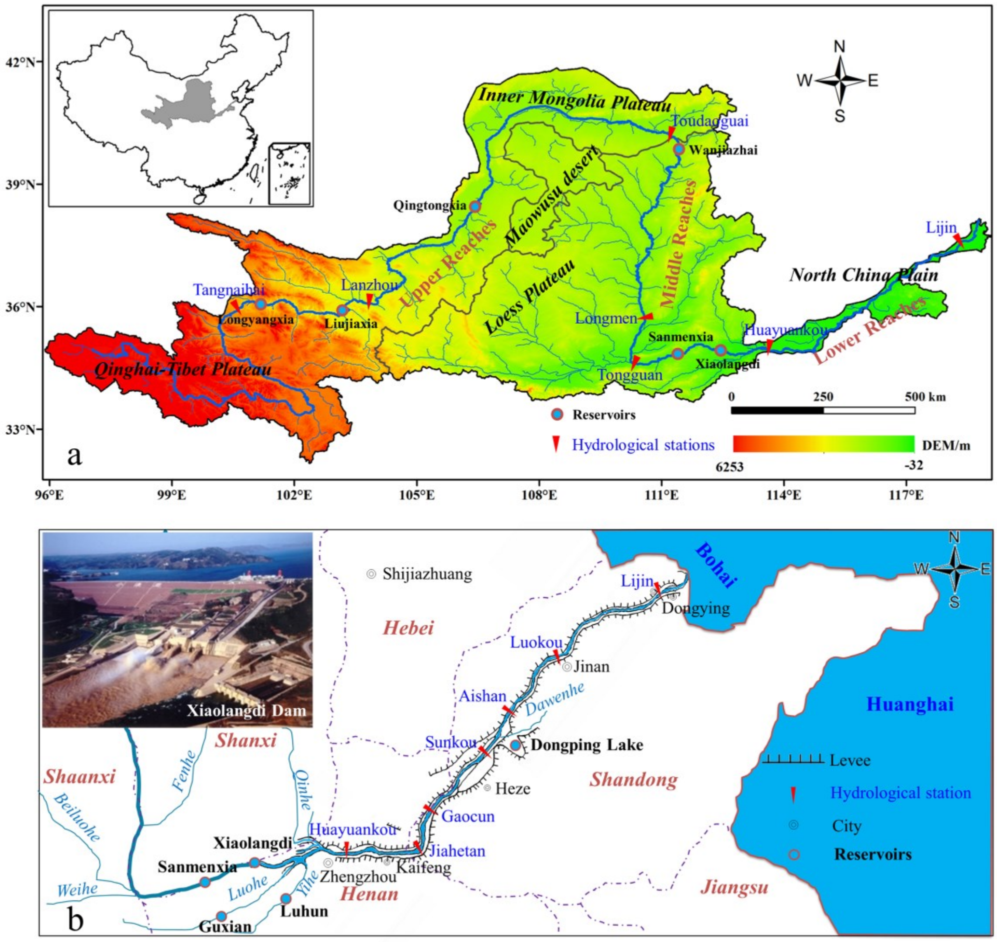

Fig. 1 Maps of the Yellow River drainage basin: (a) overall basin; (b) detailed map of LYR showing locations of main large reservoirs and key hydrological stations.

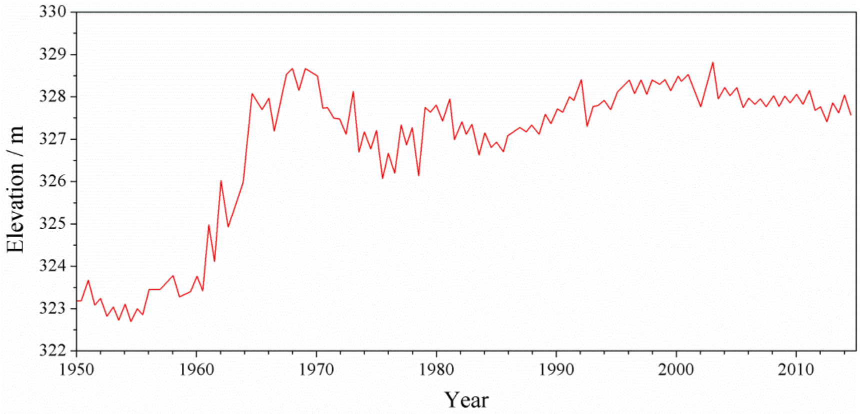

Fig. 2 Riverbed elevation at Tongguan station from 1950 to 2014.

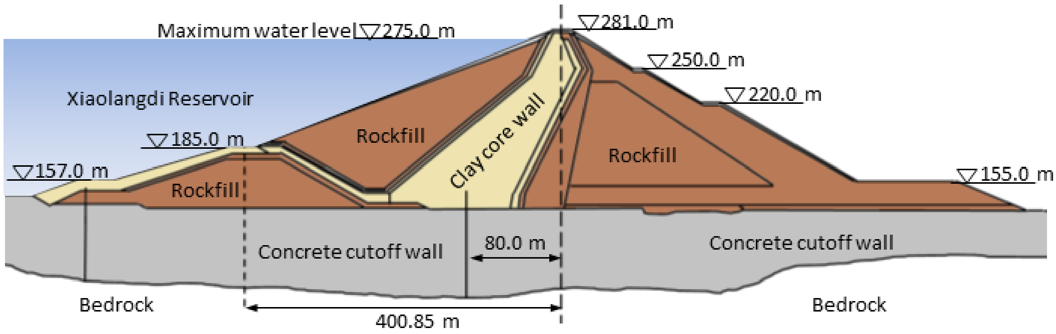

Fig. 3 A typical cross-sectional view of Xiaolangdi Dam. This diagram is adapted from Li (2009).

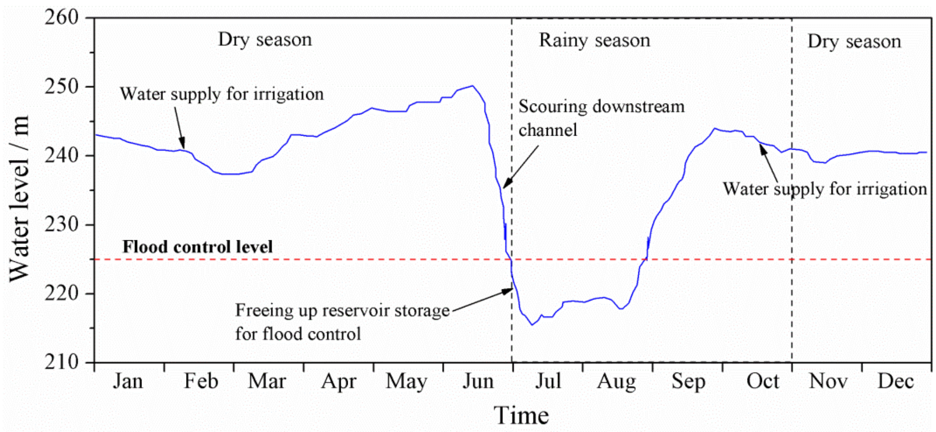

Fig. 4 Operating strategy for controlling the water level in Xiaolangdi Reservoir. Data were collected from the Yellow River Sediment Bulletin (YRSB) published by the YRCC.

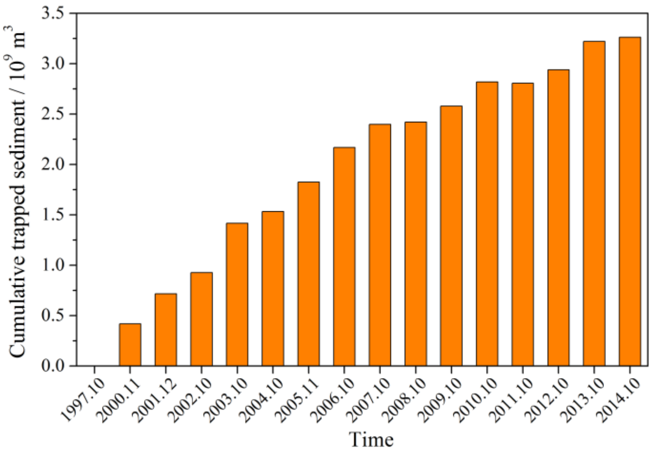

Fig. 5 Cumulative volume of sediment trapped in Xiaolangdi Reservoir since commissioning. Data collected by the YRSB and published by YRCC.

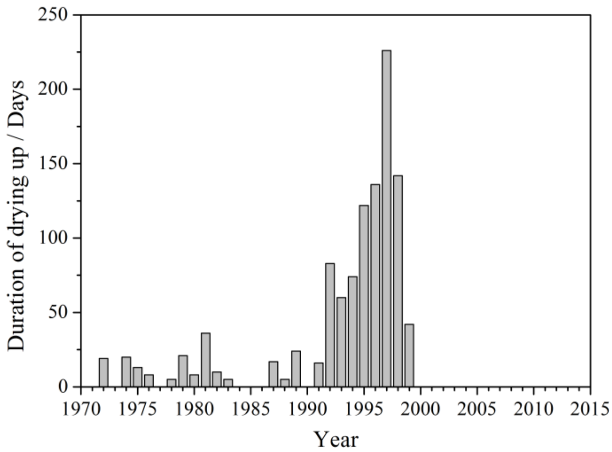

Fig. 6 No-flow days in the LYR at Lijin between 1970 and 2014.

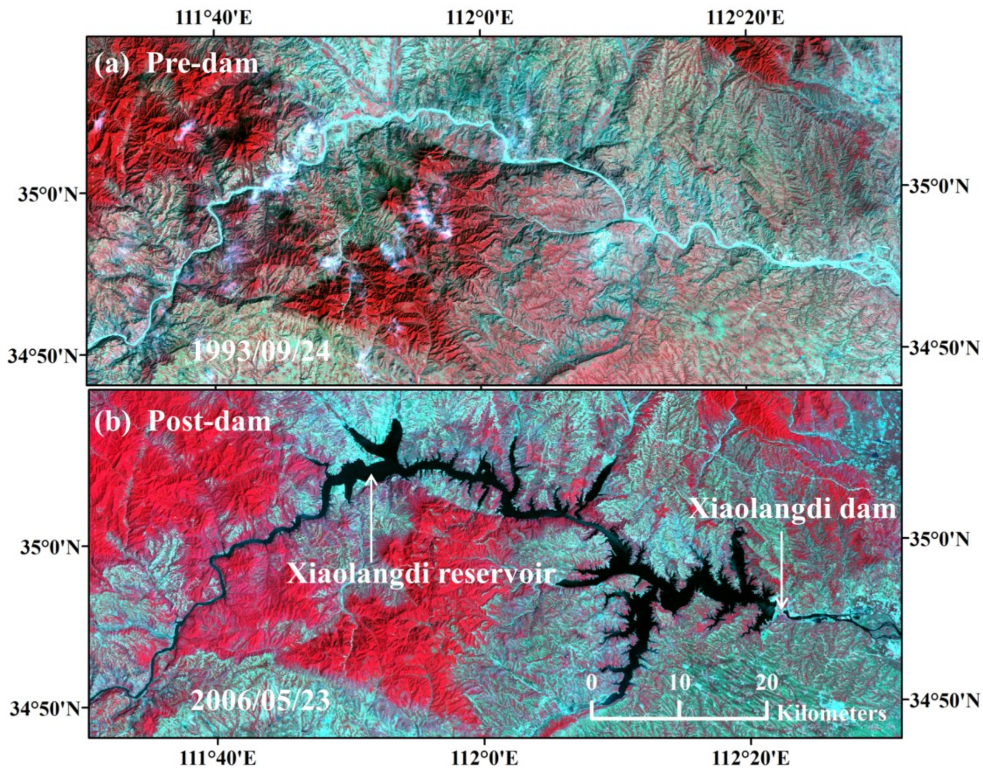

Fig. 7 Pre-dam and post-dam satellite imagery of the Xiaolangdi Reservoir region. The remotely-sensed Landsat data was archived by the Earth Resources Observation and Science (EROS) Center (http://glovis.usgs.gov/).

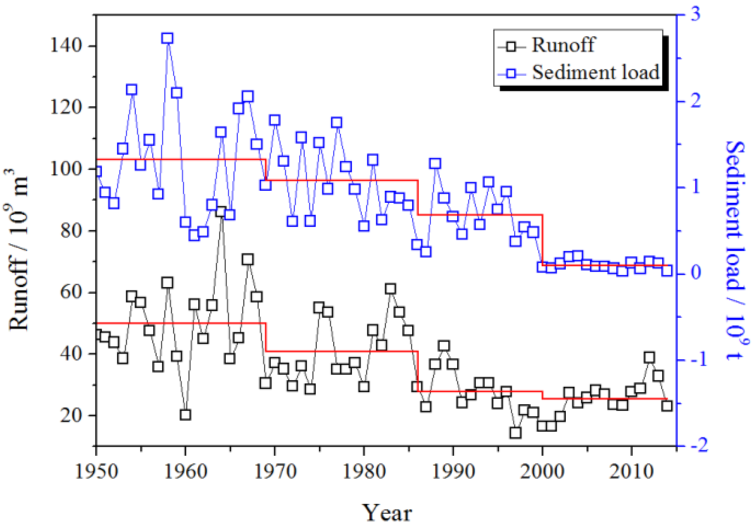

Fig. 8 Annual water discharge and sediment load at Huayuankou station from 1950 to 2014.

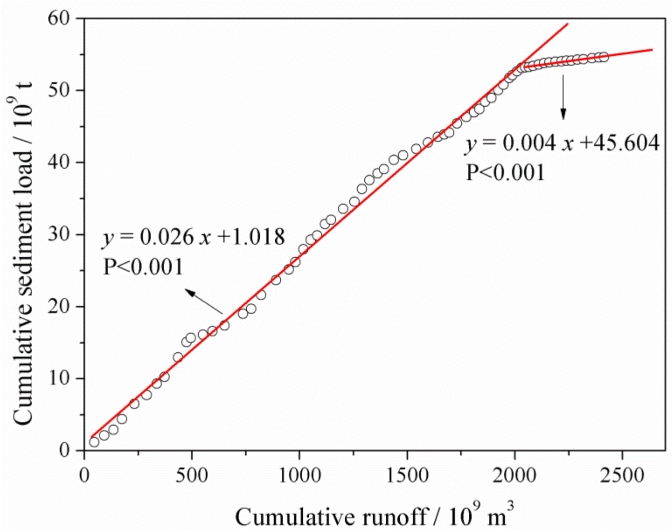

Fig. 9 Relationship between cumulative sediment load and cumulative runoff at Huayuankou station from 1950-2014.

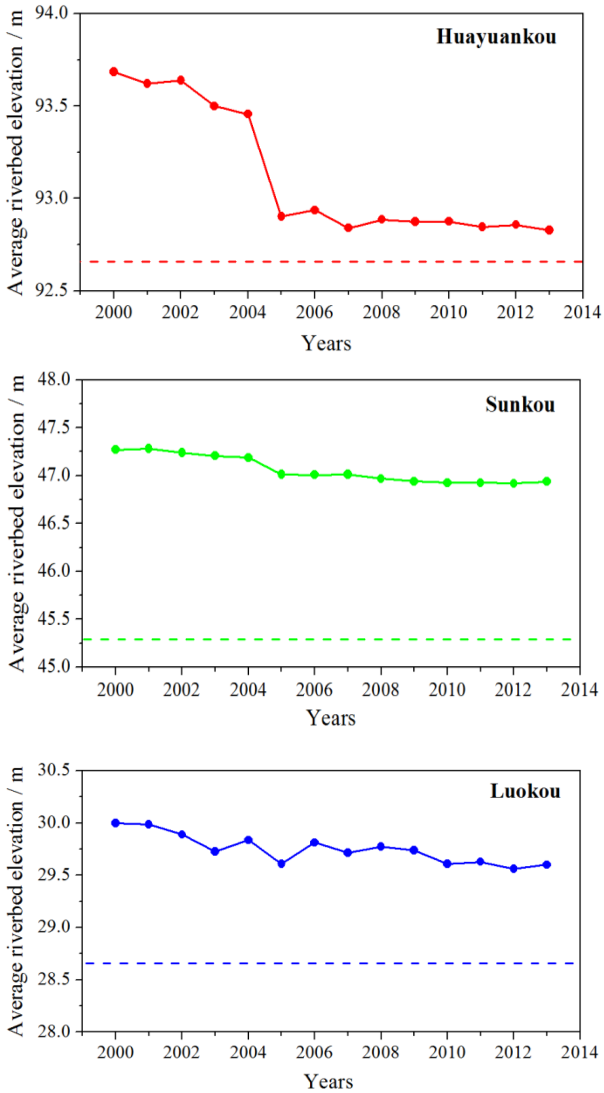

Fig. 10 Average riverbed elevation at Huayuankou, Sunkou and Luokou stations. The dashed lines represent the average riverbed elevation in the 1950s (Miao et al., 2016).

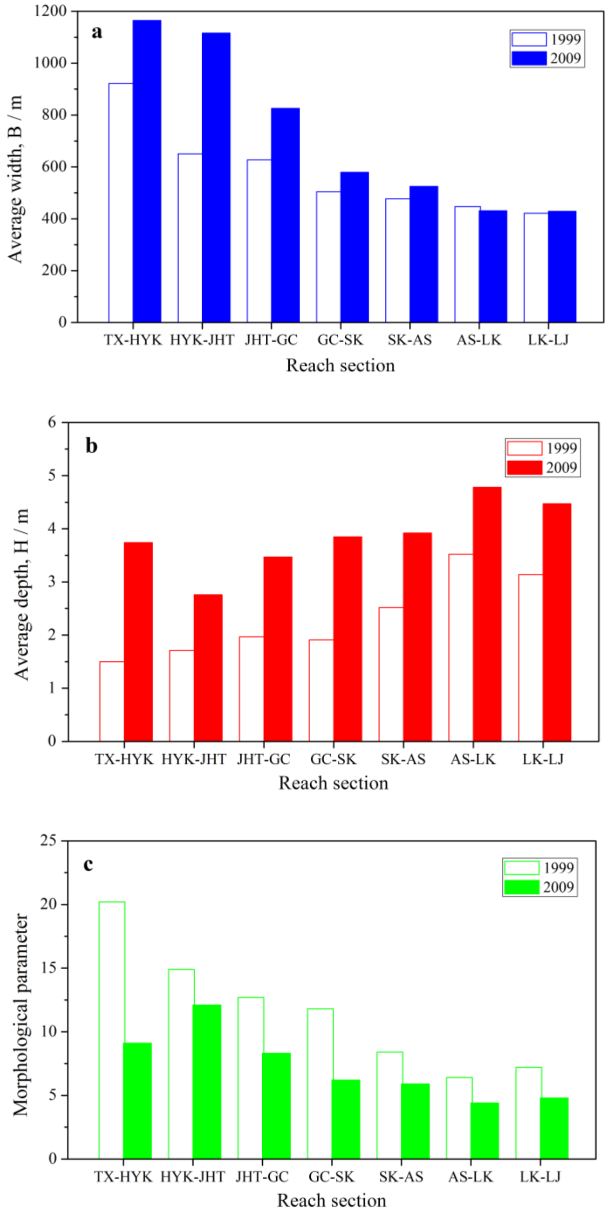

Fig. 11 Modification of river morphology from 1999 to 2009. This figure is based on data provided by Chen et al. (2012a). The morphological parameter is defined as $\sqrt{B}/H$, where B and H represent the average channel width and depth respectively.

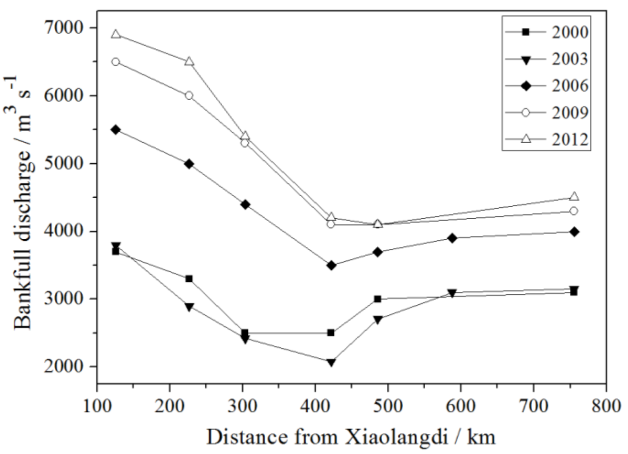

Fig. 12 Bankfull discharge profiles along the LYR in different years (Kong et al., 2015b).

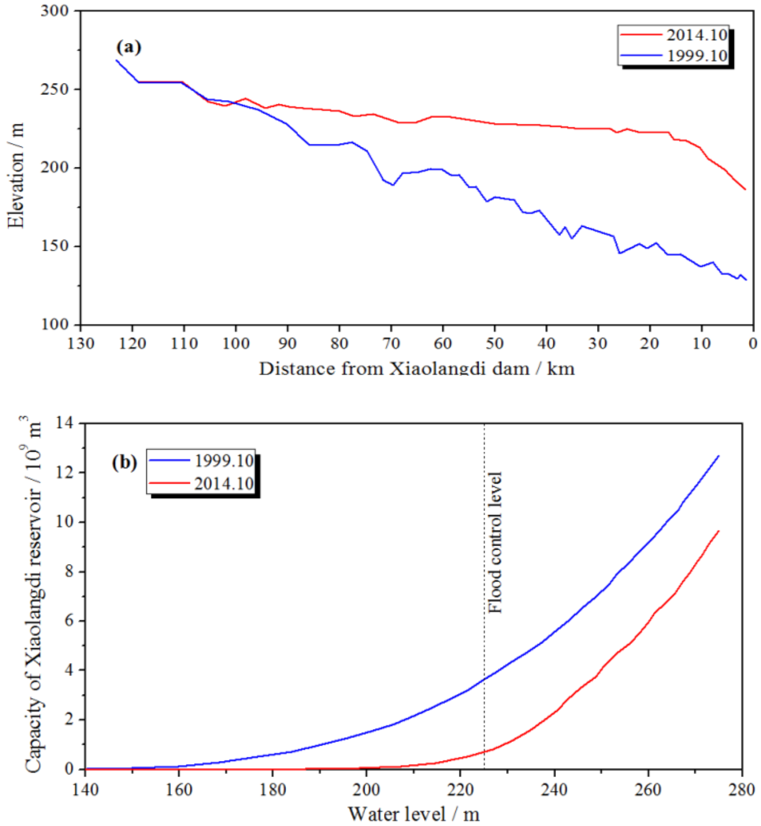

Fig. 13 Evolution of: (a) bed elevation; and (b) capacity of Xiaolangdi Reservoir.